DOCUMENT RESUME

ED 293 872 TM 011 458

AUTHOR Lippert, Renate; Finley, Fred
TITLE Students' Refinement of Knowledge during the Development of Knowledge Bases for Expert Systems.
PUB DATE Apr 88
NOTE 25p.; Paper presented at the National Association for Research in Science Teaching Conference (Lake of the Ozarks, MO, April 10-13, 1988). For a related document, see TM 011 459.
PUB TYPE Speeches/Conference Papers (150) -- Reports - Research/Technical (143)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS Cognitive Processes; *College Freshmen; *Expert Systems; Higher Education; *Instructional Innovation; *Knowledge Level; *Learning Strategies; Physics; *Problem Solving
IDENTIFIERS *Novice Knowledge Engineering

ABSTRACT

The refinement of the cognitive knowledge base was studied through exploration of the transition from novice to expert and the use of an instructional strategy called novice knowledge engineering. Six college freshmen, who were enrolled in an honors physics course, used an expert system to create questions, decisions, rules, and explanations pertaining to classical projectile motion. Construction of the knowledge base (CKB) was traced through a post-test. The progress of a particular male student, who was a confident and fluent problem solver, illustrated the progression. Integration and differentiation affected only a portion of this student's cognitive knowledge base. CKB was a practical application of new technology and research findings. The CKB process aids refinement of domain-specific knowledge due to greater degress of elaboration during encoding and greater quantity of material processed in an explicit, coherent context, and therefore in greater semantic depth. (SLD)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

ED293872

Students' refinement of knowledge during the development of knowledge bases for expert systems

U.S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)

X This document has been reproduced as received from the person or organization originating it.

☐ Minor changes have been made to improve reproduction quality.

• Points of view or opinions stated in this document do not necessarily represent official OERI position or policy.

Renate Lippert

Fred Finley

University of Minnesota

345 Peik Hall

Minneapolis, MN 55455

(612) 625-4307

"PERMISSION TO REPRODUCE THIS MATERIAL HAS BEEN GRANTED BY

RENATE LIPPERT

TO THE EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)."

Paper presented at the 1988 NARST Conference
Lake Ozark, Missourri

TM 011 458

Students' refinement of knowledge
during the development of knowledge bases for expert systems

1. Introduction

Science education attempts to impart not only domain-specific knowledge, but also domain-specific problem solving skill; unfortunately often as distinct entities. Research to date has failed to clearly identify either the cognitive mechanisms or the pedagogical approaches that cultivate problem-solving skill within contexts, let alone transfer to other contexts (Black, Swan, & Schwartz, 1988). We have not been very successful in teaching students to solve sets of problems within a domain, because of the mistaken belief and practice that students acquire problem-solving skill by observing good problem solvers, and working many problems. As a result students typically memorize the formulas and equations for the short time that they are relevant in instruction. The subsequent lack of comprehension short circuits transfer, which is particularly important for fundamental problem types that reappear with increasing complexity in various chapters, eg. projectile motion in introductory college physics.

Kinds of knowledge

Any attempt to design successful instruction in problem solving must consider what knowledge is involved in learning both the content and procedures in the domain. The distinction between declarative knowledge as propositions and procedural knowledge as productions is well known. In problem solving, declarative knowledge ("that", consisting of facts, concepts, and principles) is needed to formulate an adequate problem representation, while procedural knowledge ("how to", consisting of rules, algorithms, and procedures) is needed to execute appropriate problem-solving action with propositions. Instruction typically emphasizes either declarative or procedural knowledge, but seldom aims at integrating the two in a way that emulates real scientific thinking (Winograd & Hare, in press).

This knowledge dichotomy simplifies educational processes, but does not suffice to describe the refinement of the entire cognitive knowledge base. Recent articles have alluded to a third characterization of knowledge, namely conditional knowledge (Tennyson & Christensen, 1988), functional knowledge (Greeno, 1987; Greeno & Berger, 1987), or control knowledge (Reif, 1987). The general notion is that knowledge of applicability conditions, and consequences of actions ("when, where, and why") is crucial in the development of a coherent, interpretable and useful knowledge base. As such it is a set of propositions that states the conditions under which particular components of declarative and procedural knowledge are applicable to a given task. Therefore conditional knowledge acts as selective retrieval, matching and refining agent.

In textbook problems, conditions are often explicitly given through words like "assume", "neglect", and "approximately". However, much of such conditional knowledge of when to use specific information, and why it is significant -- the so-called utility and applicability conditions that connect factual and procedural knowledge in memory (Lewis & Anderson, 1985), is frequently left to the student to acquire incidentally over a period of time. And so teaching is usually geared only to the acquisition of knowledge, and not the refinement of it.

Kinds of refinement

Knowledge refinement entails generalization and specialization of content through restructuring activities such as differentiation and integration, generated by metacognitive knowledge and processes. Differentiation implies that more specific ideas are subsumed under more general ideas, and entails processes such as analysis of the attributes, function and application of concepts through exploration, elaboration, and explanation; and a conceptual synthesis through interpretation and extraction processes. Differentiation is therefore the addition of new propositions and/or problem-solving steps that provide more specific and detailed information within an existing set or procedure.

Integration must be preceded by differentiation, and describes the degree to which ideas are inter-related (West, Fensham, & Garrard, 1985). It entails processes such as evaluation of relationships and a procedural synthesis through the expansion or contraction of application conditions. Integration is therefore the addition of new and/or deletion of incorrect or irrelevant propositions that link various sets of previously existing propositions within or among schemata. In terms of procedural knowledge, integration entails the addition, deletion, and/or reordering of steps in problem-solving procedures.

The processes of differentiation and integration interact in that one serves as the catalyst for the other, as illustrated later.

Stages of refinement

It is very clear from the misconceptions literature that knowledge and performance are not all or none phenomena, and that partial and incomplete knowledge may more accurately characterize students' cognitive state. Characteristics of the declarative knowledge of beginning physics students are poorly differentiated concepts, imprecise propositions and a lack of conditional knowledge (Champagne, Gunstone, & Klopfer, 1985). Good students learn with understanding: they generate many explanations which refine and expand the conditions for the action parts of example solutions, and relate these actions to principles. These self-explanations are guided by accurate monitoring of their comprehension failures and successes. Such learning results in an example-independent

knowledge and in a better understanding of the principles presented (Chi, Bassok, Lewis, Reimann, & Glaser; 1987). Poorer students do not generate sufficient self-explanations, inaccurately monitor their learning and subsequently rely heavily on examples.

The expert-novice literature has typically discussed dichotomous and therefore discrete states of cognitive performance: novice or expert (Chi, Feltovich & Glaser, 1981; Larkin, 1983). It clearly simplifies the situation to say that experts use theoretical principles (eg. energy conservation) and forward chaining, while novices depend on surface features and backward chaining. Roschelle and Greeno's findings (1987) recently presented quite a different picture of expert reasoning than indicated by these studies. They found that representations of experienced subjects were strongly influenced by concrete objects in the problem, and that knowledge at various levels of abstraction can interact cumulatively in the development of an integrated representation or mental model.

The development of expert-level processes in students thus involves effective formation of both knowledge and cognitive operations. How should one teach knowledge in order to develop cognitive operations, and conversely, how does one teach cognitive operations in order to develop high quality knowledge and the ability to apply it accurately?

Requirements for the acquisition of domain expertise have been laid out by Dreyfus and Dreyfus (1986). The gist of their analysis of skill acquisition is that the transition from novice to expert entails that declarative knowledge is increasingly utilized procedurally, and that with experience within a domain, knowledge of "what-to-do-in-what-situation-at-what-juncture-and-for-what-reason" is developed. It entails a progressive evolution from analytical behavior that consciously decomposes an environment into recognizable elements, followed by abstract rule following, to concrete, intuitive behavior based on accumulation of new situations as similar to <u>whole</u> remembered ones. What is primarily involved in this evolution is conditional knowledge acquisition within specific situations, and its influence on the relationships between declarative and procedural knowledge.

They acknowledge a smooth transition between five distinguishable stages, namely novice, advanced beginner, competent, proficient, and expert. Definitive of both the novice and advanced beginner stage is behavior that recognizes learned features and applies rules deliberately and detachedly, with conscious choices of goals and decisions after reflection of alternatives. The more expert-like stages are reached when procedures are no longer purely objective and certain constellations of elements call for certain intuitive conclusions or expectations to be investigated, since memory triggers plans that worked in the past. Some analytical thinking and rule application lingers, while recognition of

similarity in terms of organization and understanding becomes prevalent. Expert-like performance is further characterized by generativity, a great deal of episodic (context-dependent) and functional knowledge (knowledge of relationships), and an awareness of progress on problems. In summary, the main features include:

1) Declarative knowledge increasingly utilized procedurally.
2) Conditional knowledge acquisition within specific situations, and its integrative influence on the relationships between declarative and procedural knowledge.
3) More intuitive problem solving, rather than detached rule following.

With reference to a given domain, the transition features described above are obviously of a longterm nature. However, learners within a particular level can display behavior that can be identified as typically novice, or competent, etcetera, for the given task and domain at hand.

Instructional strategy for knowledge refinement

To date hardly any attention has been given to the development of instructional environments in which all three kinds of knowledge can be holistically nurtured, so that a consolidated and coherent knowledge base, characteristic of experts, emerges with time. A potentially new instructional strategy, called novice knowledge engineering offers interesting insights into what students know, how they know what they know, and the interrelatedness of what they know (Bigum, 1987; Lippert, 1987a). We decided to explore the efficacy of expert systems as a teaching tool because many commercial systems offer demo disks at prices affordable by most teachers (Lippert, 1987b). This, coupled with the observation from literature that novices become para-experts as a result of knowledge engineering, provided the rationale for this study. We used an in-house expert system shell written in Turbo-Pascal (Smith, Starfield & Macneal; 1985) that interfaces with any wordprocessing editor capable of creating ASCII files. The students' tasks were to create questions, decisions, rules, and explanations to describe classical projectile motion. As such the construction of a knowledge base provided a context for domain-specific problem solving and simultaneous knowledge refinement through differentiation and integration, since students had to synthesize their knowledge about free fall, gravity, acceleration, velocity, projection angles, range, etcetera. The evolutionary changes could be seen by tracing students progress from the pretest through the construction of the knowledge base (CKB) on paper and on the computer, to the posttest.

All students reported an integration of their knowledge, and explicit awareness of the strategic value of conditional knowledge. Aspects that they had learned rotely and did not understand, and therefore could not work with, soon became evident to them,

resulting in self-evaluation of the extent, accuracy, and adequacy of their knowledge. Apart from the general features of a novice-expert transition mentioned earlier, we also found specific evidences for a slow, mediated transition in a 1) decline in errors, 2) decline in time on task, 3) change in problem and physics representations, 4) refinement of procedural knowledge seen in pattern recognition and action-sequencing, 5) development of conditional knowledge, 6) conceptual elaboration, and 7) curtailment of reasoning (issues of efficiency, conciseness, and a shift from quantitative to qualitative reasoning). To illustrate these themes, we chose data from a particular student since it best elucidates the issues from the 180 hours of observational data that this qualitative research study generated.

3. Research instruments and procedures

Our aim with the study was to explore how the different kinds of knowledge would be effected, what transitions in skill acquisition would take place, and what the nature of the refinements would be in terms of content and organization. The complete study involved six students from a representative sample of freshman honors physics. After practice in building knowledge bases in other domains, they developed knowledge bases on projectile motion ranging from 13 to 33 rules, 7 to 19 questions, and 13 to 28 decisions over the course of 16-23 hours. Sessions lasted two to three hours. Data, including thinking-aloud protocols, were collected individually and concurrently, and recorded on audio- and videotape. Pretesting occurred when they had just completed their first three weeks of formal physics instruction which had included projectile motion. The test, developed after an earlier pilot study, assessed baselines in the various kinds of knowledge. The same test was administered after the CKB process, an interval of 8 weeks wherein students did not receive any formal instruction on projectile motion, nor consulted their peers.

Declarative knowledge was elicited by a set of 12 questions that asked students to elaborate on the features of projectile motion. These protocols were converted into a "frame-slots" representation wherein frames represented the superordinate concepts, and the slots represented the subordinate or coordinate concepts. The links between these concepts were labeled with the actual productions that characterized the relationships. It was found that students' reasoning could easily be condensed into productions which contained the declarative, conditional, and procedural knowledge in the holistic manner in which it is used. These were then compared to a set of standardized productions that were taken as the minimum expected knowledge after instruction.

Procedural knowledge was elicited with 14 comprehensive problems that were presented in an increasing complexity sequence. The later problems were more open-ended and qualitative of nature. Data from these protocols enriched the declarative representation,

but was also represented in terms of a means-end-analysis format to highlight features inherent in problem solving, such as goals, actions, decisions, comments, and reasons.

Other valuable data was derived from the actual evolution of knowledge bases in terms of text files, and the decision tables and decision trees that students used as construction aids for their knowledge bases. Lastly, students gave anecdotal reports on an evaluation survey which was followed up by an interview. Questions ranged from "What was the hardest for you during the CKB", "What kind of problems can you solve now that you couldn't before?", to "What other method would have taught you comparable knowledge?" and "What is the educational benefit of CKB?" Portions of the various data sources relevant to the discussion appear in the next section.

4. Research results

Characteristics of Peter's initial problem solving skill

Peter came across as a confident and fluent problem solver. Very few instances of ignorance, diffuseness or long silences occurred. Preciseness and seemingly little cognitive effort characterized his interpretation of problems. He took less time during testing as well as the knowledge base construction than the other subjects. It was characteristic of Peter to consider concepts, relations, and methods not mentioned in the problem statement. At the time of the pretest, content such as inertial and non-inertial reference frames had not been dealt with formally, and yet he correctly solved certain problems because he was able to identify not only the existence of such reference systems, but also the discriminating features of each and their implications. Other such instances revealed how he was able to come up with an appropriate problem representation by extracting information that real novices overlooked eg.: "5000km! That's a fourth around the world. This is almost circular motion. At that distance the world is curved."

He perceived structure and relationships amongst concepts functionally and often articulated explicit application conditions that were attached to his procedural knowledge. For example, asked to predict the trajectory that a missile will follow as it moves from the North Pole to the equator, he immediately asked "Where is the observer?" thereby expressing knowledge that the location of the observer determines the observation. Peter was also capable of rich descriptions of the domain at hand, often adding little anecdotes that demonstrated his integration of world knowledge with physics. His physical intuition was well developed too so that he anticipated and evaluated outcomes without much conscious deliberations. For example, "That's a heck of a cannon! The speed of those shells is faster than sound. They'll hear them coming for sure!", or, "Seems about right for a plane", or "It seemed pretty silly that he could throw it farther up than horizontal.", or "Hitting a target 5000km away would never happen first time in the

real world, because they know there are variations in the air density and weather systems. So essentially they have missiles that adjust automatically for that." In the debriefing interview he said: "The structure of the inference engine forced me to approach the problem with a more formal, and logical strategy which I don't find natural and honestly don't use. I tend to run by intuition."

Aside from intuition, he was also generative in that he could develop and defend multiple possible solutions for unanticipated and ill-structured problems, eg. elaborating on the influence of earth's rotation and curvature on a projectile's trajectory; and also exploring the variability of gravity as a function of the earth's curvature, which is an advanced topic.

In terms of Dreyfus and Dreyfus's scheme Peter functioned at a proficient level for his peer group, but as a novice in comparison to real experts. On the pretest he couldn't solve equations that involved the calculation of angles, nor was he aware of specialized formulas he should have known, eg. the range equation and the fact that at maximum range the angle is 45 degrees. A particular problem occurred several times, namely when angle, velocity, and time had to be found as a function of each other. He was also prone to solve problems by listing the given values and possible formulas, then plugging the values into the formulas and using mathematical manipulation to come to an answer.

Overall Peter was a very capable and knowledgeable student for his level of physics instruction. Any conceptual changes were thus expected to be of a more fine grain nature. This expectation held up in our observations, though a few encouraging surprises were in store for us.

Evidences of knowledge refinement on the posttest

Peter's declarative descriptions of the domain and efficiency in problem solving during the pretest seemed to leave very little room for improvement. On closer inspection of the transcripts a general trend towards more directness and conciseness accounted for the reduction of the overall time on task. This can be largely attributed to the abandonment of the pretest strategy of listing variables, writing down appropriate equations and then plugging in known values. His preference became to identify the problem type and its associated features, and writing an equation that already contained the dimensions of the problem (characteristic of the forward chaining approaches of experts), eg. $-730 = -5(5^2) - 5vy$. Use of specialized formulas such as $y = .5at^2$ instead of the longer and more general equation of $y = .5at^2 + v0t + y0$ effectively eliminated some unnecessary steps (curtailment of reasoning). This can also be seen as a development of efficiency through pattern recognition as entire subgoals and actions are deleted. For example:

Question #	PRETEST	POSTTEST
4 (goals)	Find maximum velocity Find angle Find initial velocity Find maximum height	Find initial velocity Find maximum height
5 (actions)	A1: vx=15m/s, h=100m A2: y = -10/2t^2 + y0 A3: -100 = -5t^2 A4: t = 20s A5: x = 15x 20 m	100=5t^2 t=4.5s d = 15x4.5 = 67.5m

This can be attributed to a differentiation amongst variables in given situations, leading to a better conceptual integration of the function of the various entities.

Changes in problem and physics representations were evident from instances such as the following. "Free fall acceleration. That needs a completely different equation. I couldn't solve it earlier because I didn't know how to do it. I know now because I solved it in general for the knowledge base." In the pretest he had commented: "Free fall acceleration? Is that how much it speeds up in the fall of 200km, or is it the actual acceleration at 200km? That's a messy one." He got a value just a fraction less than at ground level and was not perturbed, seemingly because of his inability to judge the validity of the answer due to his lack of understanding of the concept of acceleration at variable altitudes. On the posttest he knew immediately which equations to apply, but made a mistake. On correcting himself ("That's way too small") he recalculated and got the right order of magnitude answer which satisfied him. In this case, refinement of a concept led to an improvement in his procedural knowledge.

Development of conditional knowledge became evident through many new associations. For example, referencing some of the key constructs of his knowledge base, namely "If you want to optimize the shelling, then change the velocity first, because the angle is related to the distance it flies, to the sine of the angle which increases slower than the velocity, and you'd have to change the angle quite a bit in order to get an equivalent response to changing the velocity. Initial vertical position is another factor, though it would affect the distance less than the angle since it doesn't influence time which is quadratic in the y-equation and disappears in the equation for maximum height."; or, "The first thing is to find out whether gravity is constant. It makes the solution a lot harder if it isn't. I'd say range must be less than 100 miles for gravity to be constant."

In another instance he switched to a qualitative propulsion argument and used constructs from his knowledge base, such as

overshooting. This shift in strategy (from the quantitative details of ballistics which were dealt with in class, to this notion of propulsion) is an example where a change in problem representation resulted in striking differences in the specific knowledge considered, and the strategies called on for solution.

Features that did not seem to have changed and therefore still characterized him as a novice in comparison to professional physicists were the prominent use of parametric equations in time and velocity, as if they constituted a problem set ("Einstellung"). This apparent lack of specialization of procedures for particular problem types meant that he sometimes failed to use the range equation which would have been more efficient and effective too. Problem and physics representations were still limited to objects, relative positions, and initial and final states, rather than underlying physics principles (such as energy conservation), due in part to the fact that this had not been stressed in instruction. Similarly, rarely were Newton's motion laws explicitly mentioned.

Instances of refinement during CKB

Without the refinement of knowledge, the product of the CKB process could not have been accomplished since it entails a significant new set of relationships that had not been dealt with in formal instruction, nor had been articulated or used during pretesting. See Peter's final knowledge base in the appendix. It shows a refinement of knowledge that does not occur at the hand of contrived textbook problems, because inference of important functional relations does not necessarily occur when students learn procedures in the absence of functional knowledge (Greeno & Berger, 1987). Peter had the fewest questions (and therefore variety of input) of all the subjects. Yet he had the most versatile and well integrated knowledge base of them all, because he was strategic in isolating the key descriptive concepts of projectile motion and then differentiating these into instantations of several projectile phenomena. He developed a more compact and coherent knowledge base by refining a limited number of concepts, rather than assimilating a broad spectrum of concepts. His decisions show how he took five concepts, namely angle, time, maximum height, velocity and distance and differentiated them to 14 variations of these basic concepts. For example:

```
velocity ->   initial, impact, vertical at impact, general vertical
max height -> from ground, from an elevation
angle ->      positive projection, negative projection, impact
time ->       general, 0 at max height, v0sin@/g at max height
distance ->   to max height, to target
```

The following discussion displays how Peter refined his concepts. The most obvious refinement event is the connection he made between velocity and projection angle. On the pretest he judged angle and initial velocity to be independent and drew a horizontal line. By

the time he was posttested he had refined this notion and could draw a graph wherein all points were possible (a grid), showing that any angle can be accompanied by any initial velocity and that one variable did not determine the other. During CKB his refinement progressed from "I have to change the 'decrease and increase angles' to 'move it closer to or further away from 45 degrees because either way you increase the range'", to "Falling short ... angle is not 45 degrees ... and velocity is not the max, then move the angle closer to 45 ... let's see, I'll try to think of some other condition ... velocity is at max ... I haven't allowed for shooting it off from different altitudes, because if you're elevated, you'd increase your range, even though you're not shooting with any vertical velocity. So I have to change the idea of the angle coming from -90 to +90 degrees. I'll have to put in other angle values, positive, but not 45 or 90 ...", as illustrated below. Other main events are the integration of elevation as a new factor determining projection (how this introduced differentiation of angle specification), consideration of impact and subsequent differentiation of velocity and distance, and differentiation of an alternate placement of the coordinate system so that time, maximum height, and horizontal distance are calculated differently.

In the account of the refinement only decisions and questions that underwent changes are listed each session. Note how precision hallmarks his refinement, eg. specification of "and/or" instead of just "and", changing of positive and negative signs for angles, and changing of coefficients for maximum height. Decisions have been rearranged to highlight clusters. Numbers of decisions are relabeled from session to session, so no significance should be attached to them in this discussion.

Peter's decision evolution

Session 1

d1: "Time = -v0sin@ +/- [(v0sin@)^2 - 2a*s0y] / a".

d9: "Time at maximum height = v0sin@/a".
d10: "Maximum height = 3/2[v0sin@]^2 + s0y".
d11:"Horizontal distance at maximum height=(v0^2)sin@cos@/a + s0x".

d8: "Move angle towards 45".
d4: "Move angle away from 45 and/or decrease v0".
d3: "Move angle towards 45 or increase v0".

d7: "Increase v0".

Session 2
Integration of s0y (elevation) factor causing angle differentiation

d4: "Move angle away from +45 and/or decrease v0 and/or s0y".
d3: "Move angle towards +45, increase v0 and/or s0y".

d8: "Move angle towards +45".
d5: "Move angle towards -90".

d13:"Increase v0 and/or s0y".

Session 3
Further integration of s0y factor

d11:"Increase s0y and/or move angle closer to +45".
d12:"Increase s0y".
d13:"Decrease s0y".
d14:"Decrease s0y and/or v0".
d15:"Decrease s0y and/or move angle away from +45".

d16:"Decrease v0 and/or move angle away from +45".

Session 4
Integration of distance and alternate coordinate system

d3: "Distance to target = v0cos@ {-v0sin@ +/- [(v0sin@)^2 + 2a*(s0y)]/-a}".
d4: "Set parameters so that distance = -a(t^2)/2 + v0sin@ + s0y".

d21: "Time at maximum height is 0".
d22: "Maximum height is s0y".
d23: "Horizontal distance at maximum height is 0".

d25: "Maximum height = 3/4 [(v0sin@)^2]/a + s0y".

Session 5
Differentiation of impact

d25: "Maximum height = 1/2 [(v0sin@)^2]/a + s0y".

d27: "Vertical velocity at impact = - [(v0sin@)^2 - 2a*s0y]".
d3: "Velocity at impact = - [(v0sin@)^2 - 2a*s0y + (v0cos@)^2]".
d4: "Angle of impact = arctan([(v0sin@)^2 - 2a*s0y]/v0cos@)".

<u>Peter's question evolution</u>

Questions were refined simultaneously with the decisions. Observe therefore how Question 2 Session 2 shows the differentiation of angles, and how in Session 3 Question 4 from Session 1 was separated into two questions (4: issues of impact and 6: issues of maximum height) because they had previously been combined. In Session 2 Question 5 introduced the new elevation factor. In Session 4 the other new factor, distance to target, was brought in via Question 7.

Session 1

```
Q1: "Is projectile:"
a1 "Overshooting"
 2 "Hitting target"
 3 "Falling short".

Q2: "Is angle"
a1 "0"
 2 "45"
 3 "90"
 4 "Something else

Q3: "Is velocity"
a1 "0"
 2 "At maximum"
 3 "In between".

Q4: "Do you need to know:"
a1 "Time to impact"
 2 "Velocity and/or angle to impact in a given time"
 3 "Time at maximum height"
 4 "Maximum height"
 5 "Horizontal distance at maximum height"
 6 "None of the above".
```

Session 2

```
Q2: "Is angle:"
a1 "0"
 2"+45"
 3 "+90"
 4 "-90"
 5 "+, not +45 or +90"
 6 "-, but not -90".

Q5: "Is launch pad's initial vertical position:"
a1 "Above ground, but not at maximum height"
 2 "At ground level"
 3 "Underground"
 4 "At maximum height".
```

Session 3

```
Q4: "Do you need to know:"
a1 "Time to impact"
 2 "Velocity and/or angle to impact in a given time"
 3 "None of the above".

Q6: "Do you need to know:"
a1 "Time at maximum height"
 2 "Maximum height"
 3 "Horizontal distance at maximum height"
 4 "None of the above".
```

Session 4

```
Q7: "Is distance to target known?"
a1 "Yes"
 2 "No".
```

As can be seen, unifying his various concepts led Peter to develop several general formulas that are not to be found in a textbook.

This testifies to his generative abilities, level of comprehension, and ability to capture projectile motion in mathematical language. Space does not allow to relate the many other instances of refinement, nor a description of how the rules evolved. He started the on-line phase with four questions, 12 decisions, and 12 rules. Altogether he came up with 83 new components (7 questions, 31 decisions, 45 rules). What is characteristic of Peter is that he used very few questions to create relatively many rules, indicative of the interconnectivity of concepts he constructed through differentiation. Complexity became a result not of the quantity, but a combination of both the quality and quantity of relations.

In summary one can say that a refinement in his knowledge as a result of the CKB process did take place, both in the declarative and the procedural domain, leaving him with a coordinated relational framework he did not manifest before. For example, the refinement of the concepts of time and maximum height when he introduced negative angles; or the gradual differentiation of the concept of time in flight to include time at maximum height, and time at impact. He was able to articulate the relationship between projection angle and initial velocity, could generate a procedural representation of that relationship via formulas, and recognized when that relationship was critical. Often refinement was the direct result of deliberate attention to conditional knowledge, such as "Is projection occurring ground to ground, or are launch and target vertically displaced? This can be further supported from independent comments he made on the evaluation survey, and subsequent interview. (R: Renate, P: Peter)

R: Describe to me how you would have learned projectile motion if you hadn't built a knowledge base.

P: I'd just have an equation memorized, like I basically do for angular motion problems. If it comes out, I don't know if it's right or not. But by working with the things there, you have a better idea of what's reasonable. I would probably never even have a second thought about what the angle has to do with the velocity, or what any of that has to do with the time it takes to hit a certain point in the trajectory.

R: So you wouldn't have made those connections, those relationships?

P: Not unless I was forced to for some reason, and then that would go in one ear and out the other. You either have to learn everything from it by spending a lot of time on it or spend a little time on it and not really do anything with it. What I learned about projectile motion was that some of the interrelationships of variables within the projectile motion equations, affect the result more than others, and therefore are more important. It'd be, like, the angle versus velocity, which one would change, would affect the ... outcome more. Velocity is more important than the angle. An angle is more important than initial height.

R: What kind of problems can you solve now that you wouldn't have been able to do before?

P: Those with multiple unknowns, tying, say, different equations together, tying together different ideas. But my organization still stinks. I can do, say, one, or two, or three at a time. I can't see the whole picture all, all at once.

R: How did you feel about the problems now on the posttest versus on the pretest?

P: I think I could do 'em faster. It took a lot less time and I think I was more accurate in doing 'em.

R: And what do you ascribe it to?

P: It just seems to be easier to visualize what's going on. I could even draw out those pictures of how the angle affects, say, the distance and the time. And I can do that for all the variables. So you just get this idea of how if one variable changes, how the rest of them will change. The interrelatedness of the things.

In summary, integration and differentiation affected only a portion of his cognitive knowledge base. Although the on-line knowledge base was by far not representative of what he knows (though representative of what he can quantizise) it was encouraging to see that even the "best" student in the study showed refinement of knowledge. That a student with such a good initial conceptual framework does benefit from this instructional method, but needs 16 hours to complete a knowledge base of the discussed size, illustrates that the process of knowledge refinement is not a trivial matter at any level of cognitive complexity. Instruction had failed to display or foster the conceptualization of fundamental relationships in the domain, and left him with an unorganized understanding. Else it would not have taken him this much time to establish a critical functional relationship between three key concepts in projectile motion (initial velocity, elevation, and projection angle), and know how they vary and effect the nature of projection.

At face value, the domain of projectile motion appears well structured. In reality, the CKB process revealed that due to the large number of variables and the resulting combinatorial explosion, it became an ill-structured problem. The irony of it all is that these students were honors students, and that all of them deemed this domain an easy one, suggesting that they would have shown more significant learning in a "difficult" domain such as rotational dynamics. If the process of integrating knowledge on such a small scale and to no profound depth takes this long, it is no wonder that true expert knowledge and problem solving within a domain takes years to acquire.

4. Conclusion

Often students do not perform as we would like them to because both the knowledge and associated cognitive processes are inadequately taught. The result is that many mistakes exhibited by students are traceable to knowledge that is fragmented and uninterpretable, while the deficient cognitive functions most often encountered in novice behavior are 1) unsystematic exploration, 2) inadequacy in experiencing and defining an actual problem, 3) restricted inferential thinking, 4) impaired strategies for hypotheses testing, and 5) inadequate communication of the outcome of elaboration (Sternberg, 1985). We were satisfied that our initial observations during a pilot study with a different set of students had held out in this study, namely that domain-specific problem solving invariably led to a refinement of the three kinds of knowledge within the learning environment created by knowledge engineering. The CKB process aids refinement of domain-specific knowledge due to greater degrees of elaboration during encoding, greater quantity of material processed in an explicit, coherent context, and therefore in greater semantic depth. Students are taught a thinking/learning strategy that forces systematic exploration, planning, and evaluation. Since relationships, rather than loose facts are stressed, they are taught the value of reconstruction and design, rather than rote, detailed recall from memory. This positively effects transfer potential.

As instructional strategy CKB is a practical application of new technology and an integration of various research themes. As a teaching strategy, it blends the acquisition of knowledge and an experience base, with the nurture of the higher-order thinking skills. It is a new process to trace changes in cognitive structure as a result of instruction, allows for individualization as well as cooperative learning, and promises to be effective in identifying and confronting misconceptions (Lippert, 1987c). The fact that students actually see their own cognitive knowledge base in operation is an advantage that this learning strategy offers. It is also a promising testing procedure to replace traditional tests that are insensitive to structure, errors of omission and intrusions. Finally, it has the potential to increase fundamental understanding of science learning, and to yield new views of teaching and curriculum goals.

The themes touched upon in this study blend with current work by Greeno, Reif, Chi and others on the role of elaboration, problem types and generative processes in problem representations as an extension of the work by Gestalt psychologist such as Duncker and Wertheimer. The data also supports Larkin and Simon's (1987) conjecture that students are unable to solve problems in part because they learn principles without translating them into inference rules. Studies of this nature can help researchers understand the thought processes that underlie effective student learning and then to translate these findings into improved

teaching practices. Findings can contribute to the refinement of cognitive learning theories by clarifying processes by which complete structures of knowledge are acquired and modified.

Other issues not addressed in this paper, but very well represented in the data were the acquisition of cognitive strategies, and the function of metacognition and cognitive structure.

Acknowledgement

The financial assistance of the Institute for Research Development of the Human Sciences Research Council of South Africa, and the College of Education, University of Minnesota, toward this research is hereby acknowledged.

Appendix: Peter's final knowledge base

```
Context: This knowledge base was written to help solve equations
relating to simple ballistic motion, unaffected by forces other
than a constant acceleration in one direction.  It can solve for
time to impact, distance to target, angle of incidence and velocity
at impact, maximum height, and time at maximum height; it has
diagnostics explaining what parameters to change to hit a target,
and has comments to deal with unrealistic situations.  (All
equations are ideals, and never happen exactly in reality, except
by accident.)".

r1: if q1a2 & q4a1 then d1.
w"Time can be found from position equation if variables are right."

r2: if q1a2 & q4a2 then d2.
w"Velocity and angle are related to time, distance, and inital
vertical position mathematically."

r31: if q1a2 & q4a3 then d3.
w"Velocity at impact is related to angle of projection, initial
velocity, and initial vertical position."

r32: if q1a2 & ( q2a1 or q2a2 or q2a5 or q2a6 ) & q4a4 then d4.
w"Angle at impact is related to angle of projection, initial
velocity, and initial vertical position."

r33: if q1a2 & ( q2a3 or q2a4) & q4a4 then d5.
w"If projectile is shot straight up, it comes straight down."

r3: if q1a3 & not q2a2 & (q3a1 or q3a3) & not q5a4 then d17.
w"Maximum range occurs at +45, maximum initial vertical position
and maximum velocity."

r4: if q1a1 & (q2a1 or q2a2) & (q3a2 or q3a3) & (q5a4 or q5a1) then
    d18.
w"Range decreases as initial vertical position decreases, velocity
decreases and/or angle moves away from +45."

r28:if q1a1 & (q2a5 or q2a6) & (q3a2 or q3a3) & (q5a4 or q5a1)
    then d18.
w"Range decreases as initial vertical position decreases, velocity
decreases and/or angle moves away from +45."

r5: if q1a1 & q2a4 then d9.
w"If V=0 and/or the angle is +90 or -90, range=0 and it's
impossible to overshoot under these conditions, even if you are
shooting at yourself."

r21: if q1a1 & q2a3 then d9.
w"If V=0 and/or the angle is +90 or -90, range=0 and it is
impossible to overshoot under these conditions, even if you are
```

```
shooting at yourself."

r22: if q1a1 & q3a1 & not q5a3 then d9.
w"If V=0 and/or the angle is +90 or -90, range=0 and it is
impossible to overshoot under these conditions, even if you are
shooting at yourself."

r23: if q1a1 & q5a2 & q2a1 then d9.
w"If V=0 and/or the angle is +90 or -90, range=0 and it is
impossible to overshoot under these conditions, even if you are
shooting at yourself."

r24: if q1a1 & q5a2 & q2a6 then d9.
w"If V=0 and/or the angle is +90 or -90, range=0 and it is
impossible to overshoot under these conditions, even if you are
shooting at yourself."

r6: if q1a3 & q2a2 & q3a2 & q5a4 then d20.
w"Maximum range occurs at Vmax, Soymax, and angle of +45, if you
are still undershooting it is too far away to hit."

r7: if q1a3 & q2a2 & (q3a1 or q3a3) & q5a4 then d21.
w"Maximum range occurs at angle +45, Soymax and Vmax, range can be
increased by increasing the velocity."

r8: if q1a3 & (q2a1 or q2a3 or q2a5) & q3a2 & q5a4 then d8.
w"Maximum range occurs at angle +45, Soymax and Vmax, range can be
increased by moving the angle closer to +45."

r9: if q1a3 & q2a2 & not q3a2 & not q5a4 then d10.
w"Maximum range occurs at angle +45, Soymax, and Vomax, range can
be increased by increasing Vo and/or Soy"

r10: if q1a3 & not q2a2 & q3a2 & not q5a4 then d11.
w"Maximum range occurs at angle +45, Soymax, and Vomax; range can
be increased by moving the angle closer to +45 and/or increasing
Soy."

r11: if q1a3 & q2a2 & q3a2 & not q5a4 then d12.
w"Maximum range occurs at angle +45, Soymax, and Vomax, range can
be increased by increasing Soy."

r17: if q1a1 & q2a2 & q3a2 & (q5a1 or q5a4) then d13.
w"Because range is dependent on initial vertical position."

r18: if q1a1 & q2a2 & not q3a2 & (q5a1 or q5a4) then d14.
w"Because range is dependent on initial velocity & initial vertical
position."

r19: if q1a1 & not q2a2 & q3a2 & (q5a1 or q5a4) then d15.
w"Because range is dependent on angle and initial vertical
position."
```

```
r20: if q1a1 & not q2a2 & not q3a2 & q5a2 then d16.
w"Because range is dependent on angle and initial velocity."

r12: if q6a1 & ( q2a2 or q2a3 or q2a5 ) then d24.
w"Velocity is 0 at maximum height so the velocity equals
acceleration due to gravity at a given time (t)."

r25: if q6a1 & ( q2a1 or q2a4 or q2a6 ) then d26.
w"When angle is non-positive, maximum height occur at time 0."

r13: if q6a2 & (q2a2 or q2a3 or q2a5) then d25.
w"Vertical position is related to initial velocity, angle, initial
position, and time."

r26: if q6a2 & (q2a1 or q2a4 or q2a6) then d22.
w"When angle is non-positive, initial vertical position is also the
maximum vertical position."

r14: if q6a3 & (q2a2 or q2a3 or q2a5) then d28.
w"Horizontal position is related to initial velocity, angle, time,
and initial horizontal position."

r27: if q6a3 & (q2a1 or q2a4 or q2a6) then d23.
w"When angle is non-positive, maximum height occurs at initial
position and distance is therefore 0."

r15: if q6a4 then d27.
w"I really might not know. (Don't talk to me about life.)"

r16: if (not q1a2) & q5a3 then d19.
w"To determine if you are underground."

r29: if q1a2 & q7a2 then d7.
w"I can tell you distance to target if you don't know it."

r30: if q7a1 then d6.
w"I can tell you how to hit the target if you know it."


d1:"Time = -VoSin@ +/- Sqrt[( VoSin@ )^2 + 2a*(Soy - Sy)] / -a".
d2:"VoSin@ = [(a/2)*T^2 + Soy - S] / T".
!!!"Vertical velocity at impact = - Sqrt[ (VoSin@)^2 - 2aSoy ]".
d3:"Velocity at impact = -Sqrt[(VoSin@)^2 + 2a*Soy + (VoCos@)^2 ]".
d4:"Angle of incidence = Arctan{Sqrt[(VoSin@)^2 - 2a*Soy]/VoCos@}".
d5:"Angle of incidence = +90".
d6:"Set parameters so that distance = -a(t^2)/2 + VoSin@ + Soy".
d7:"Distance to target = VoCos@ {-VoSin@ +/- Sqrt [(VoSin@)^2 +
  2a*(Soy)]/-a}".
d8:"Move angle towards +45.".
d9:"You're shooting in the wrong direction -- re-aim.".
d10:"Increase Vo and/or Soy.".
```

```
d11:"Increase Soy and/or move angle closer to +45.".
d12:"Increase Soy.".
d13:"Decrease Soy.".
d14:"Decrease Soy and/or Vo.".
d15:"Decrease Soy and/or move angle away from +45.".
d16:"Decrease Vo and/or move angle away from +45.".
d17:"Move angle towards +45 and/or increase Vo and/or Soy.".
d18:"Move angle away from +45 and/or decrease Vo and/or Soy.".
d19:"You can't hit anything underground.  Try shooting above
ground.".
d20:"Target is too far away and is impossible to hit.".
d21:"Increase initial velocity.".
d22:"Maximum height is Soy.".
d23:"Horizontal distance at maximum height is 0".
d24:"Time at maximum height = VoSin@ / a".
d25:"Maximum height = 1/2 [( VoSin@ )^2]/a + Soy".
d26:"Time at maximum height is 0.".
d27:"I don't understand what you want to know. (Really, I don't.)".
d28:"Horizontal distance at maximum height = (Vo^2)Sin@Cos@ / a".

Q1: "Is projectile:"
w"To determine if your variables are correct, or what (if anything)
is wrong."
a1 "Overshooting"
2 "Hitting target, or not trying to hit the target"
3 "Falling short".

Q2: "Is angle of projection:"
w"It affects the range."
a1 "0"
2 "+45"
3 "+90"
4 "-90"
5 "Positive, but not +45 or +90"
6 "Negative, but not -90".

Q3: "Is velocity:"
w"It affects the range."
a1 "0"
2 "At maximum"
3 "In between".

Q4: "Do you need to know:"
w"To determine what you want to know, and whether I know how to
derive it."
A1 "Time to impact"
2 "Velocity and/or angle to impact in a given time"
3 "Velocity at impact"
4 "Angle of incidence at impact"
5 "None of the above".
```

```
Q5: "Is launch pad's initial vertical position:"
w"Initial position affects range."
A1 "Above ground, but not at maximum height"
 2 "At ground level"
 3 "Underground (Surrounded by dirt on all sides and on top)"
 4 "At maximum height".

q6: "Do you need to know:"
w"You don't need to be able to hit the target to find these things,
so I can tell you how to derive them."
a1 "Time at maximum height"
2 "Maximum height"
3 "Horizontal distance from launch site at maximum height"
4 "None of the above".

Q7: "Is horizontal distance (Sx) to target known?"
w"It is much easier to hit the target if you know how far away it
is."
a1 "Yes"
2 "No"
3 "It doesn't matter".
```

References

Bigum, C. (1987). Expert Systems in Educational Research. Educational Computing Research Group, Deakin University, Australia.

Champagne, A.B., Gunstone, R.F., & Klopfer, L.E. (1985). Instructional Consequences of Students' Knowledge about Physical Phenomena. In L.H.T. West & A.L. Pines (Eds.), Cognitive Structure and Conceptual Change. New York: Academic Press.

Chi, M.T.H., Feltovich, P.J., & Glaser, R. (1981). Categorization and Representation of Physics Problems by Experts and Novices. Cognitive Science, 5, 121-152.

Chi, M.T.H., Bassok, M., Lewis, M.W., Reimann, P., & Glaser, R. (1987). Self-explanations: How students study and use examples in learning to solve problems. Learning Resource and Development Center, University of Pittsburgh, Technical Report #9.

Dreyfus, H.L. & Dreyfus, S.E. (1986). Mind over Machine. New York: The Free Press.

Greeno, J.G. (1987). Generative Processes in Representations of Problems. Office of Naval Research Report # N00014-85-K-0095.

Greeno, J.G. & Berger, D. (1987). A Model of Functional Knowledge and Insight. Office of Naval Research Report # N00014-85-K-0095.

Larkin, J. (1983). Expert representations of physics problems. In D. Gentner & A. Stevens (Eds.), Mental Models. Hillsdale, NJ: Lawrence Erlbaum Associates.

Larkin, J.H. & Simon, H.A. (1987). Why a diagram is sometimes worth a thousand words. Cognitive Science, 11, 65-99.

Lewis, M.W. & Anderson, J.R. (1985). Discrimination of Operator Schemata in Problem Solving: Learning from Examples. Cognitive Psychology, 17, 26-65.

Lippert, R.C. (1987a). Teaching Problem Solving in Mathematics and Science with Expert Systems. School Science and Mathematics, 87(6), 477-493.

Lippert, R.C. (1987b). Selecting Expert System Shells For Classroom Use: Criteria and Guidelines. Computers in Human Behavior, 3, 145-149.

Lippert, R.C. (1987c). Development of Expert Systems: An Instructional Strategy for Dealing with Misconceptions. Proceedings of the Second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics, Volume 1, Cornell University, Ithaca, NY.

Reif, F. (1987). Cognitive principles for instructional design. Office of Naval Research Report # N00014-83-K-0598.

Roschelle, J. & Greeno, J.G. (1987). Mental Models in Expert Physics Reasoning. Office of Naval Research Report # N00014-85-K-0095.

Smith, K.A., Starfield, A.M., & Macneal, R. (1985). Constructing Knowledge Bases: A Methodology for Learning to Synthesize. Proceedings of the 1985 Frontiers in Education Conference.

Sternberg, R.J. (1985). Instrumental and componential approaches to the nature and training of intelligence. In S.F. Chipman, J.W. Segal, & R. Glaser (Eds.), Thinking and Learning Skills, Vol. 2. Hillsdale, NJ: Lawrence Erlbaum Associates.

Tennyson, R.D. & Christensen, D.L. (1988). MAIS: An Intelligent Learning. In D.H. Jonassen (Ed.), Instructional Design for Microcomputer Courseware. Hillsdale, NJ: Lawrence Erlbaum Associates.

Trollip, S.R. & Lippert, R.C. (1988). Construction of Knowledge Bases: A Process for Instruction. In M. Chignell, P.A. Hancock, & A. Loewenthal (Eds.), Intelligent Interfaces: Theory, Research, and Design. North Holland Press.

West, L.T.H., Fensham, P.J., & Garrard, J.E. (1985). Describing Structures of Learners Following Instruction in Chemistry. In L.T.H. West & A.L. Pines (Eds.), Cognitive Structure and Conceptual Change. New York: Academic Press.

Winograd, P.N. & Hare, V.C. (in press). Direct instruction of reading comprehension strategies: The role of teacher explanations. In E. Goetz, P. Alexander, & C. Weinstein (Eds.), Learning and study strategies: Issues in assessment, instruction and evaluation. Hillsdale, NJ: Lawrence Erlbaum Associates.